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REPORT

MRL-R-952

SPECTROSCOPIC STUDIES OF A RAILGUN MUZZLE FLASH

D.D. Richardson

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ABSTRACT

In this report we demonstrate the powerful information which is obtainable from spectroscopic observations of the muzzle flash of a railgun. Spectra observed in the range 335 to 460 nm are presented and shown to be very complex. From identification of about 90 of the significant lines, a temperature of 30-35,000 K is estimated for the muzzle flash. From observations of Al lines, due to placement of Al plugs at varying distances from the muzzle, and the subsequent injection of atoms into the railgun plasma, we are able to show that Al remains within the plasma for at least ten plasma lengths. The Al concentration tends to decrease as a quadratic function of distance.

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SPECTROSCOPIC STUDIES OF A RAILGUN MUZZLE FLASH

1. INTRODUCTION

This paper reports spectral analysis of the muzzle flash of the MRL railgun RAPID [1]. The experiments for this analysis were designated the RMF series, and were performed from 13-3-84 to 10-4-84. The object was to obtain information on the physical properties of the plasma armature of the gun and forms part of our studies aimed at understanding the nature and properties of plasma armatures in railguns. Attempts were first made to obtain and analyse spectra from inside the railgun bore but this proved too complex at this stage of the studies. We have overcome many of the difficulties by a study of the spectral emission of the muzzle flash, which comprises a plasma of much lower temperature and pressure. It is still found, at least for some radiations, to be optically opaque, however. (The optical path length is less than the dimensions of the plasma.)

Because of the lower temperatures and pressures in the muzzle flash (the plasma expands adiabatically on exit from the bore), the spectrum has many emission lines, and usually some self-reversal lines. There is some continuum radiation, but it is much less than the in-bore result. The spectrum has many qualitative similarities to the "plasma puff" result, where we observed the light from plasma passing through a hole in the side of the barrel as the armature passed down the bore, but which we do not discuss further here. (These observations are based on the results of the RPUF series of experiments done at MRL during mid-1983 [10].)

The experiments are based on the concept of introducing aluminium atoms into the railgun plasma at specified distances from the gun muzzle, and looking for the presence of Al ions in the muzzle flash by spectroscopic means. Varying the position at which Al is introduced yields information on the rate at which material is being removed from the plasma as it progresses down the barrel. In addition, analysis of the spectra obtained yields physical information on the muzzle flash, and by inference, some limits on the properties of the railgun plasma.

Two phenomena have been considered in detail in our experiments. We have firstly considered the presence of aluminium in the plasma, as a result of it being deposited into the plasma at controlled distances from the muzzle. This gives us insight into the residence period of certain material in the plasma, particularly when that material is collected as a result of rail damage. Secondly, we have attempted to identify as many lines in the spectrum as possible. An estimate of temperature has been made from the species present, as well as showing how to obtain a better estimate from the relative intensities of some lines.

In what follows we describe the experimental details and this is succeeded by an analysis of the results, and a discussion of the significance of the data obtained. We conclude with an analysis of possible further work using this technique and mention some additional information which might be obtained.

2. EXPERIMENTAL DETAILS

The spectra were measured with a Jarrel-Ash 75-000 0.75 m focal length grating spectrograph with grating rulings of 590.5 lines/mm (15000 lines/inch). The spectra observed covered the approximate wavelength range 330 to 460 nm. Spectra were recorded on Ilford HP5 film force developed in Microphen to give a rating of 6400 ASA.

The spectrograph was aligned so that light from the muzzle flash at 20-30 mm from the muzzle entered the slit after focussing with a single 300 mm focal length 50 mm diameter plane-convex lens. The lens was made of ultra-violet transparent Herasil fused silica, and placed approximately 150 mm from the muzzle region and perpendicular to the bore axis. The spectrograph slit was set to 40 micrometres.

A reference spectrum was superimposed on the photographic film for each experiment. The reference was obtained from an atomic absorption Fe hollow cathode reference lamp, and was placed on the film to overlap the experimental spectrum. The instrument was not moved or adjusted between the time the reference spectrum was exposed, and the experiment performed, except for the opening and closing of the shutter. The film was held steady in the film holder by applying a vacuum to the holder plate. In this manner accurate measurements for the observed spectral lines were obtained.

Fe was chosen as the reference because of the proliferation of spectral lines in the wavelength range of interest [2]. This permitted accurate determination of the wavelengths of lines observed in the muzzle flash spectra, and hence more reliable identification of the origins of the observed lines. In general, we were able to determine wavelengths to an accuracy of better than +/- 0.05 nm (0.5 Angstroms). Tables of spectra were used to identify the atomic or ionic species with a given line [2,3,4].

The gun was constructed with 99.95% pure copper rails and the Al was introduced into the plasma as follows: Tapered holes were drilled in the pairs of rails at a pre-determined distance from the muzzle in each case, and Al plugs inserted by immersing them in liquid nitrogen and tapping into place. The plugs were machined flush with the rail surface. The gun plasma was initiated by applying a capacitor voltage of 6 kV across a Cu foil weighing approximately 0.1 g placed with the projectile at 50 mm from the breech (the barrel length was 500 mm). As the plasma and projectile pass down the barrel past the Al plug, material from the plug surface is drawn into the plasma as a consequence of the arc damage processes on the rails [5]. The same conditions were used for each experiment to ensure that the current in the gun at shot-out was approximately the same for all firings, and hence the plasma conditions in the muzzle flash, apart from Al content, were similar in all cases.

The projectiles, made of Lexan (polycarbonate), were machined at the back to provide good obturation. This was done by milling a V-shaped groove along each of the four back edges so that under pressure the edges would expand and seal the bore. Using this technique little or no plasma escaped from behind the projectile during a firing, and plasma pressures could be assumed to be similar in each case. Our measurements of muzzle voltage, which can be used to indicate plasma by-passing [6], confirmed that leakage was minimal.

The muzzle volt probes, attached to the rail ends at the muzzle, were originally held in place with brass screws. It was found that these screws suffered some damage during firing, and therefore may have contributed to the observed spectrum. They were therefore replaced by pointed probes pressed onto the rails from through the insulator body of the gun, close to the muzzle. In this manner, reliable voltage measurements were made with no contamination of the plasma possible. For each firing both breech and muzzle volts and gun current were monitored.

3. RESULTS

To assist in the identification of the elemental species present in the muzzle flash spectrum, an analysis of the composition of the materials used in the gun was undertaken. The results of the analysis are given in Table I which shows percentage elemental compositions for the Al plugs, the polycarbonate gun body, the glue used to attach the Cu foil to the polycarbonate projectile, and the Cu gun rails. The analyses were performed by either X-ray fluorescence or by arc or spark spectroscopy, and were done by the Electrochemistry Group at MRL. These techniques do not show up lighter elements such as C, O or N, which are probably also present.

We conclude from Table I that there should be only very small traces of metals other than Cu in our muzzle flash spectra, apart from the introduced Al, of course. We might also expect to see some evidence of Fe, Pb, Bi, Si, P

and Br. Because of the polycarbonate body and the fact that firings were done in air, there could also be evidence of the elements C, O, N and possibly H.

Because of the complexity of the spectra observed, we have not been able to complete a comprehensive analysis. We present below, however, the analysis done so far, including the likely identifications of some 90 lines between 350 nm and 460 nm.

To assist in determining which ion species are most likely present in the spectra, we have compiled a table of ionisation energies of the elements which predominate in Table I. These values are shown in Table II, where the energies are given both in electron volts and in degrees Kelvin. Using the rough rule of thumb [9] that the equilibrium temperature is one fifth of the ionisation potential, we also show in Table II the estimated temperatures required for the particular ionisation to occur. From unpublished estimates based on computer modelling carried out at MRL, we believe the in-bore plasma to have a temperature in the range of 30,000 to 70,000 K. The lower end of this range is more likely.

In all, eleven experiments were performed, although several were required to solve technical difficulties. Seven different positions for the aluminium plugs relative to the muzzle were studied, as well as an experiment with no plugs at all, to provide the 'reference' measurement. Prints of the spectra for each of these eight experiments are shown in Fig. 1.

The spectra were analysed in some detail using a Baird-Atomic microphotometer, Model RC-3. Using this instrument, it was possible to generally identify wavelengths to +/- 0.05 nm or better, as well as being able to measure line intensities where desired.

The spectra shown in Fig. 1 each displayed well over 100 emission lines, as well as several absorption (self-reversal) lines. Not all have been identified, but approximately 90 have been assigned wavelengths and probable identifications. These are listed in Table III. In some cases more than one identification is possible, while in others we have not been able to determine the line's origin. The reference data was obtained primarily from refs. 2-4. Identifications were based on both wavelength and line intensities. Some lines may also be attributed to vibrational and rotational states of chemical compounds, though we have not been able to confirm this.

A glance at the spectra of Fig. 1 will reveal that there is little direct correspondence between the Fe reference spectrum, and the muzzle flash spectrum. Therefore we conclude that there is essentially no Fe in the muzzle flash. This statement is supported by the very small amounts of Fe shown in Table I. The fact that only a small number of the prominent Fe spectrum lines may be present as shown in Table III adds strength to the belief that almost certainly none are. We therefore suggest that the identification of Fe lines as shown in Table III is probably incorrect.

We also point out that we have found very little evidence to suggest that any Mg, Si, S or Br are present, though some of these elements have only

weak or few lines in this region of the spectrum. There is stronger evidence to suggest that Phosphorus is detected, along with the more likely species of N I, O I, O II, C I, Al I, Al II, Cu I, Cu II. There are also indications in the spectra of traces of N II, Al III and C II. If there is indeed Al III present, this would imply, from Table II, a temperature in the muzzle flash of at least 44,000 K. A more likely figure is obtained from the observations of O II, giving a temperature of at least 32,000 K, a figure which is similar to other estimates [10]. The temperature within the bore would be much higher since the muzzle flash comprises gases which have undergone adiabatic expansion. Assuming, for example, an expansion of a factor of 30 in volume, with an estimated factor of 10 reduction in pressure, the temperature within the bore would be three times our estimate, or up to 90,000 K. Since we cannot be sure of the changes in volume and pressure on exit from the bore, this temperature estimate within the bore is subject to large errors. The most accurate statement that can be made is that the in-bore plasma has a temperature of at least 30,000 K. Experiments at MRL, where the spectrum of the plasma within the bore have been studied, have shown that strong continuum radiation is emitted, Fig. 2, and there is very little sign of single transition lines in the spectrum. This implies that temperatures and pressures are indeed significantly higher within the bore.

We have studied the variations of the intensity of the Al lines at 396.153 and 394.396 nm in the spectra of Fig. 1 in some detail. Since for each of the experiments (except RMF 3) the Al plug was a different distance from the muzzle, we expect the concentrations of Al in the muzzle flash to vary. This gives an indication of how and how quickly material is added to and removed from the plasma within the gun.

The intensities of the two lines were measured by finding the percent transmission of light through the lines on the film, compared to the background transmission from the film, using the microphotometer referred to earlier. These raw film density data were then analysed to produce information on the Al concentrations, as follows.

The line intensities corrected for the background on the film were estimated by [11]

$$\log I_{corr} = \log I_{meas} - [\log (\frac{I_{meas}}{I_b}) - \log (\frac{I_{meas}}{I_b} - 1)] \qquad (1)$$

where I_{meas} is the measured line intensity, and I_b is the background value near to the measured line. The corrected intensity was found from the antilogarithm of eqn. (1). The measured and corrected intensities are shown in Table IV. It is then assumed that the corrected intensity is proportional to the concentration of emitters, the proportionality constant being the product of Planck's constant and the frequency.

We show in Fig. 3 the result of our analysis, as a plot of square root of intensity versus distance of the Al source (plugs) from the muzzle, for the two Al I lines at 396.153 and 394.396 nm. We have also performed the same analysis for the experiment (RMF 3) where we did not use any Al plugs at all. In the latter case we found some faint residual lines at approximately

the same wavelengths. The square root intensities for the two wavelengths were found to be 0.040 and 0.049 for the 394.396 and 396.153 nm lines, respectively. The origin of the material producing these lines is unknown, but conjectured to be trace quantities of aluminium present in the gun components. Though the Lexan insulation in the barrel was carefully cleaned between shots, it is possible that there were residual amounts of Al implanted in the surface of the insulation. New rail surfaces were used for each shot, eliminating possible contamination from that source.

Results, similar to Fig. 3 can be obtained by plotting the intensity against other functions of distance. For example, the relationship between the logarithm of a residual intensity and distance is approximately linear; the residual intensity is defined as the difference in intensity between when an Al plug is present and when it is absent.

Within the accuracy of the measurements, both curves shown in Fig. 3 are approximately linear. That is, we may say that the concentration tends to decrease as a quadratic function in distance. At large distances (greater than 200 mm) from the muzzle, there is clear evidence that the concentrations do not decrease indefinitely. This may be the result of our analysis; no attempt has been made to account for the non-linearity of our film with light intensity variations. Several methods for doing this are documented [11] but since we were unable to do an accurate calibration test on our film, it was not clear which of the correction formulae should apply. Likewise, no account was taken of possible residual amounts of Al in the gun, as evidenced by the RMF 3 (no Al plugs) result already mentioned.

The evidence in Fig. 3 suggests that almost all of the Al injected at the plug has been removed before the plasma has travelled 200 mm. Since, from photographic evidence [6], the plasma has a length of 20-25 mm in RAPID, our results suggest that material in the railgun plasma is replenished only within about ten plasma lengths, and may never be completely extracted from the plasma.

We have considered the possibility of making an estimate of the muzzle flash temperature from the measured intensities of the two Al I lines at 394.396 nm (λ_1) and 396.153 nm (λ_2). The temperature T can be found from [12]

$$kT = \frac{E_2 - E_1}{\ln\left[\frac{I_1}{I_2}\left(\frac{\lambda_1}{\lambda_2}\right)^3 \frac{g_1}{g_2}\frac{f_1}{f_2}\right]} \qquad (2)$$

Where E is the line excitation energy, I is the intensity, λ its wavelength, g its statistical weight and f its oscillator strength. The subscript refers to the particular line in the aluminium doublet, k is Boltzmann's constant and ln the natural logarithm.

For our two lines of interest, the measured intensities are given in Table IV, while we know that $g_1 = 2.0$ $g_2 = 1.333$ [13]. The oscillator

strengths, or f-numbers have recently been determined [14] to be $f_1 = 0.115 +/- 0.001$ and $f_2 = 0.116 +/- 0.001$. The excitation energy difference E_2-E_1 is found to be 112.051 cm^{-1} [14], or 161.22 K.

For all realistic values of muzzle and in-bore temperatures, the argument of the logarithm in eqn. 2 must be close to unity. Thus small variations in the parameters give large variations in the logarithm. Substituting the constants listed above and our experimentally derived intensities, unrealistic temperatures (some of which are negative) are derived from eqn. 2.

We conclude therefore, that to use eqn. 2 as a temperature estimate, we require measurements of intensities of lines with much greater values of E_2-E_1. This usually means the lines should be much further apart in wavelength. Problems then arise with the wavelength-dependent response of the film, but useful results should be possible with accurate calibration of the film with neutral density filters and a UV lamp.

4. DISCUSSION AND CONCLUSIONS

We have used spectroscopic methods to make some detailed measurements of the properties of the plasma in the muzzle flash of the RAPID railgun. The method yields a very complex spectrum of both emission and self-reversal lines. This paper reports a preliminary analysis of the spectra. The only other known report of spectroscopic studies on a railgun, ref [9], was for the arc seen on shot-out of a solid armature projectile in the ANU railgun. Our results study the plasma of a plasma armature railgun.

From the identification of lines in the spectra, we have been able to conclude that the observed degree of ionisation of the plasma species present suggests a muzzle flash temperature in the region of 30-35,000 K. This is in apparent agreement with previous unpublished determinations by other means.

We have studied the effects of injecting aluminium into the plasma at varying distances from the muzzle. We have found that the Al concentration in the plasma tends to decrease as a quadratic function of distance of travel in the bore. Further, we have found that the concentration of Al is significantly reduced only after about 200 mm, or ten plasma lengths, and that traces of material may remain for substantially longer distances.

Our experiments were designed to ensure that the current in the plasma on exit from the gun was as nearly the same in all experiments as possible. This meant that muzzle flash temperatures and pressures should have been nearly the same for each experiment. Unfortunately, because of the manner in which the current varies within the gun during a firing, the current within the plasma would not have been the same for each of the Al plug

positions used. This means that the quantity of Al evaporated into the gun plasma may have varied, and we are unable to account for this simply. With a muzzle velocity of 1 km/s and a firing time of 1 ms, it takes about 50 μs to travel 50 mm. Using this we can estimate the time for the plasma to move from the plug to the muzzle. From our record of current flow during the firings, we can therefore estimate the current in the gun at each plug. When this is done, we find that the current at the 250 mm plug was at least 1.5 times that at the 50 mm plug. The quantity of material extracted from the surface might be expected to be proportional to the power, or current since the voltage is approximately constant. Thus we may have as much as 50% more Al initially in the plasma for the 250 mm shot than for the 50 mm shot.

It is difficult to conceive of a design for an experiment to avoid this problem. If we do it so that the current at each plug is the same, the current at shot-out will vary, affecting significantly the muzzle flash properties and making comparison of the spectra difficult. Ideally what is required is a set-up where the current at the plug is always the same, and the current at shot-out is the same each time. [In fact, there may be strong advantages in having zero current at shot-out.]

An additional interesting result of our experiments is the apparent absence of any Paschen-Back or Zeeman splitting of the spectra lines due to the magnetic fields present. We make our measurements generally perpendicular to the field generated by the current in the rails and plasma, and thus one might expect to see line splitting, and to be able to infer magnetic field strengths. The fact that we have not found any splitting, at the resolution of our experiments, suggests that either no (or little) magnetic field lines extend beyond the muzzle, or that the plasma acts to exclude magnetic fields from its centre. It is possible that both these things happen.

An estimate of the spectral splitting due to the magnetic field can be derived by assuming a constant magnetic field within the bore of 30 Tesla, and take this as the field in the region of the muzzle flash, also. From the expression for the frequency shift due to the Normal Zeeman Effect [15] and a field of 30 T, we estimate the Al line at 394.396 nm to have a frequency shift of $+/- 4.2 \times 10^{11}$ s^{-1}. This translates into the wavelength doublet at 394.5 and 394.9 nm. That is, we have a total split between the two polarised lines, caused by the magnetic field of 0.4 nm, a value which is well within the resolution of our experiments. We would, of course, expect many lines to be split by the field, and they should all have a separation of similar magnitude. The anomolous Zeeman effect will complicate the line structures and splittings, but will not alter our conclusion that though we might expect to find Zeeman splitting, it has not, in fact, been observed.

We have described how measured line intensities may be used to estimate temperature in the muzzle flash plasma, but our limited analysis has not made such estimates feasible. Calibration of the photographic film, and approximate intensity-wavelength corrections [11] are required, as well as intensity measurements for lines with large differences in excitation energies. Better results would also probably be obtained by using copper line intensities, since more of these are available over a wider wavelength range. One tantalising prospect, however, is that of being able to determine the Al atom temperature as a function of the plug position.

The results and analysis described here are only preliminary; much more detailed studies of the spectra we have obtained are required. For example, we have made no determinations of line widths, and apart from the two Al I lines described above, have not attempted to measure and relate line intensities. More detailed analysis will permit more accurate temperature estimates and also provide an estimate of the pressure in the plasma at the point of observation.

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TABLE I

Elemental analysis of railgun components (% composition)

Al plugs	Cu 5	Fe 0.7	Si 0.4	Zn 0.3	Pb 0.6	Bi 0.6	Mg 0.11
Polycarbonate	Si (variable)	Br 1	traces S,P,(Fe)				
Glue	P 0.1-0.5						
Cu rails	Cu 99.95						

TABLE II

Ionisation energies for some of the expected ion species in the muzzle flash, and an estimate of the required temperature for their appearance

Ion	Ionisation Energy (eV)	Ionisation Energy (10^3 K)	Ref.	Estimated Temperature to ionise (10^3 K)
C I	11.267	130.7	[7]	26
C II	24.383	283	[7]	57
N I	14.54	169	[8]	34
O I	13.61	158	[8]	32
O II	35.146	408	[8]	82
Mg I	7.64	89	[8]	18
Al I	5.986	69	[7]	14
Al II	18.828	218	[7]	44
Al III	28.44	330	[7]	66
Si I	8.15	95	[8]	19
P I	10.55	122	[8]	25
P II	19.65	228	[7]	46
S I	10.36	120	[8]	24
Cu I	7.726	62	[7]	12
Cu II	20.292	164	[7]	33
Br I	11.84	137	[8]	27

T A B L E III

Observed muzzle flash spectral lines for the Al plug at 150 mm from the muzzle. Wavelengths are in nm. These are tentative identifications only

Estimated	Identification
457.063	P II 456.521
455.817	Cu II 455.5922
454.149	Cu I 453.9695, P 454.020, 454,112
453.237	Cu I 453.0819
450.59-451.03	
448.087	Cu I 448.0359
444.695	N II 444.7035, Fe 444.7722
442.748	P 442.815, Fe 442.7312
441.525	Cu I 441.560
441.024	C 441.006
437.854	Cu I 437.820
437.131-437.465	C bh 437.14
436.631	O II 436.6906, Br 436.560
434.907	O II 434.9435
432.849	O II 432.862, 432.747
432.571	O II 432.576, Fe 432.5765
431.681-431.904	
431.959	O II 431.9647
431.848	O II 431.7160, C II 431.742
430.791	
427.566	Cu I 427.5131
426.120-427.232	
424.952	Cu I 424.8957
422.727	Al II 422.6809
421.460	N I 421.473
418.946	S II 418.971, O II 418.9793
418.501	O II 418.5453, Fe 418.4895
417.722	Cu I 417.7758
416.276	
415.220	O II 415.3310, S II 415.3098
413.162	
411.839	Fe 411.8549
410.449	O II 410.473, N I 410.998, Fe I 410.4128, air 410.34
407.112-407.557	Cu I 407.5588
406.890	O II 406.9903, 406.9635
406.278	Cu I 406.2698
404.276	Cu I 404.350
402.271	Cu I 402.2657
399.490	N II 399.4995
397.321	O II 397.3266
396.821	
396.153	Al I 396.1527
394.396	Al I 394.4032
393.317	Cu I 393.2917
392.137	Cu I 392.5274, 392.1267
391.70-391.482	

TABLE III
(Continued)

390.636	Fe 390.6482
390.258	Fe 390.2948
389.947	Fe 389.9709
389.535	Fe 389.5658
388.327	C bh 388.34, weak O II
387.577	C II 387.6409
386.158	Cu I 386.1746
385.797	Fe 385.6373, weak O II, N II
385.602	
385.074	Fe 385.0820, 384.9969
380.570	Cu I 380.530, 380.0502
375.925	Cu I 375.9492
374.924	Cu II 374.8203
373.723	Fe 373.7133, weak Al II
372.700	O II 372.730, Fe 372.7621
371.254	Cu I 371.2009
370.642	P II 370.605
369.919	Cu I 370.0536
368.585	Cu II 368.6555
365.932	weak Cu, Br
365.598	Cu I 365.5859
363.629	Cu I 363.5916
362.739	Cu I 362.733
362.094	Cu I 362.0352
361.353	Cu I 361.4218, 361.3761
361.275	Al 361.2467
360.204-360.180	Cu I,II 360.2032, Al III 360.162
359.870	Cu I 359.9140
359.091	weak C, CII
358.646	Al II 358.6548, 358.6692, 358.6802, 358.7057 358.908
353.345	Cu I 353.3746
353.062	Cu I 353.0386
352.711	Cu I 352.7482
352.377	Cu I 352.4239
351.988	Cu I 352.0031
351.209	Cu I 351.2121, Bi I 351.0853
348.318	Cu I 348.3761
347.517	Cu I 347.5999
346.611	Fe 346.5863
345.498	Cu I 345.4686
345.053	Cu I 345.0332
343.719	N II 343.7162
342.273	
341.550	Cu I 341.578
340.438	P II 340.433
340.159	Cu I 340.2244
338.046	Cu I 338.1421, 338.1124
336.489	Cu I 336.5349
336.044	C II 336.1051

bh = band head

T A B L E IV

Results of intensity measurements on 1.) Al I 394.396 nm (I_1), and 2.) Al I 396.153 nm (I_2), and background intensities, I_b. Corrected intensities are also shown [11]. Intensities in arbitrary units based on percent transmission

Experiment RMF	(mm)	394.396 nm I_1	I_b	396.153 nm I_2	I_b	Corrected I_{1corr}	I_{2corr}
8	50	13.0	1.64	18.5	1.72	11.35	16.8
7	125	6.1	1.75	8.85	1.80	4.3	7.05
6	150	6.7	2.04	9.6	2.10	4.7	7.5
11	175	5.1	1.79	6.4	1.85	3.3	4.5
4	200	4.65	2.50	5.15	2.50	2.15	2.7
10	225	3.5	1.60	4.1	1.60	1.9	2.5
9	250	3.9	2.15	4.5	2.17	1.7	2.4
3	-	1.3	1.14	1.4	1.14	0.16	0.24

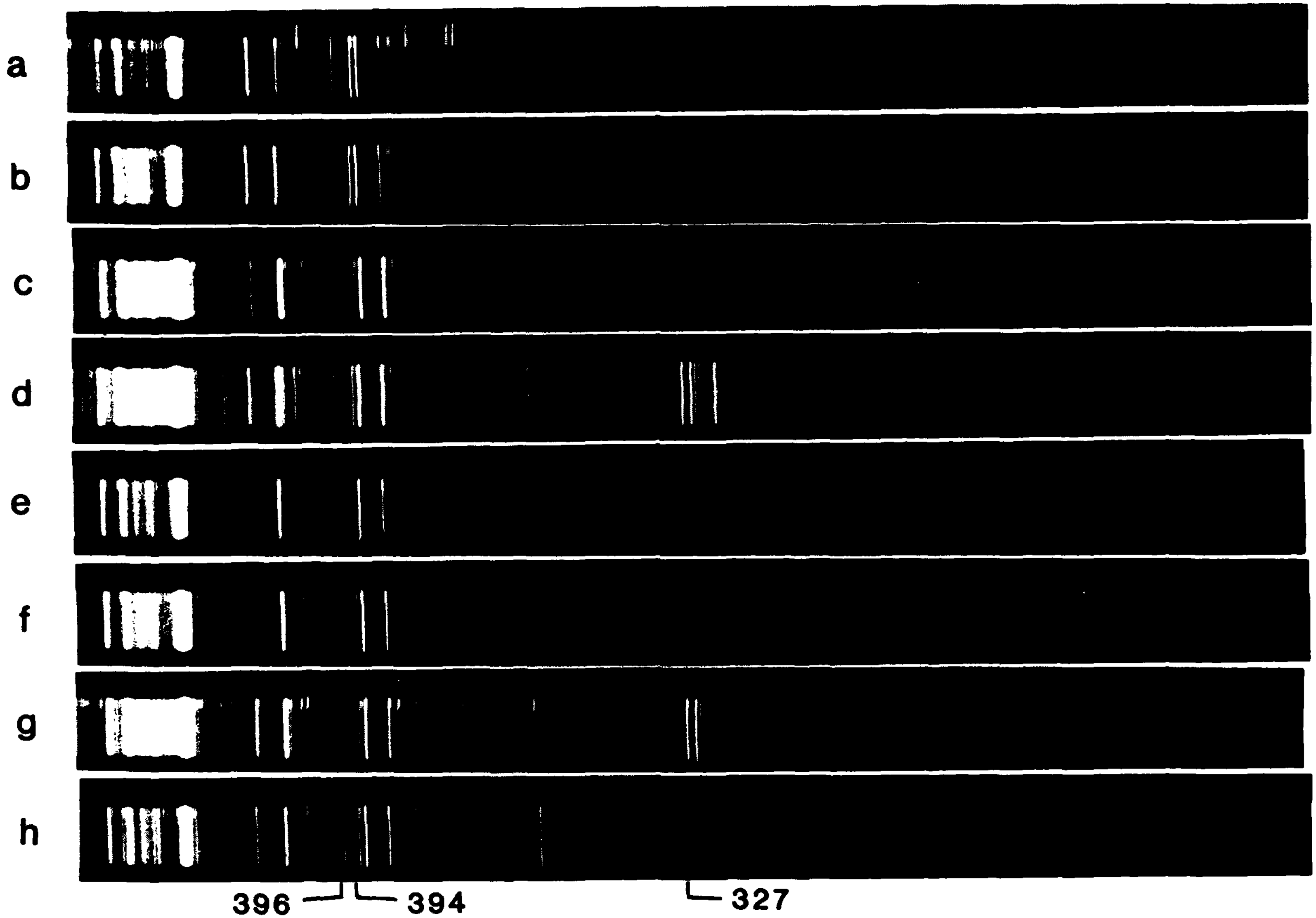

Figure 1. Muzzle flash spectra obtained from the RMF series of experiments. In all cases, an Fe AA lamp spectrum is superimposed. Wavelength range is 460 to less than 335 nm. The spectra shown are as follows:
(a) RMF 3, no plug present (b) RMF 9, plug 200 mm from muzzle (c) RMF 10, 225 mm
(d) RMF 4, 200 mm (e) RMF 11, 175 mm (f) RMF 6, 150 mm (g) RMF 7, 125 mm
(h)RMF 8, 50 mm

Figure 2. Spectrographic record of light emitted from the pl-sma within the bore of the RAPID railgun. the spectrum was observed through a Herasil window placed in tne body of the gun. (The spurious lines at the short wavelength end of this spectrum are thought to arise from the muzzle flash.) Reference lines of Hg are also shown.

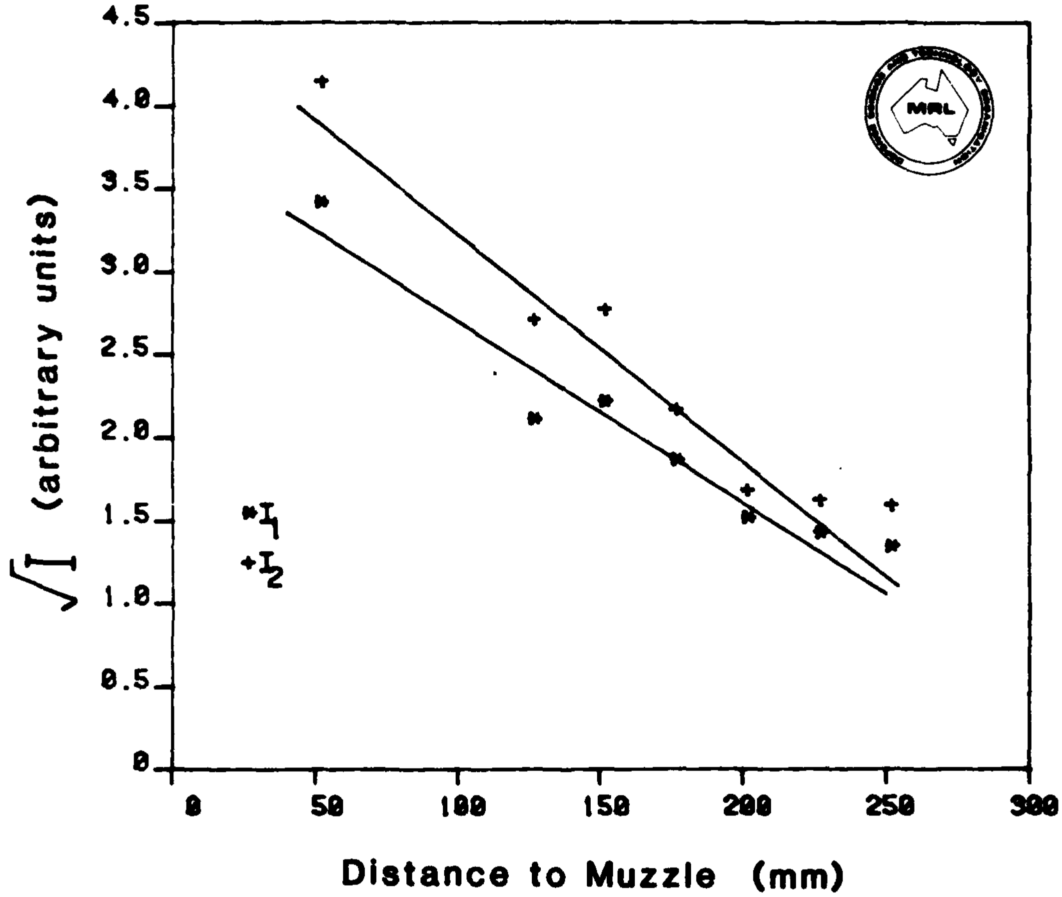

Figure 3. Plot of the square root of corrected line intensities versus distance of the Al source from the muzzle. Results for emission lines at 1.) 394.396 nm and 2.) 396.153 nm due to Al I are presented. The curves give a representation of the change in the Al concentration in the muzzle flash.